A simulation model for prediction of rain-on-snow melt recovery

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A SIMULATION MODEL FOR PREDICTION OF RAIN-ON-SNOW MELT RECOVERY

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1.0 Executive Summary

Snowmelt caused by rain-on-snow (ROS) causes serious flooding and economic loss in the Pacific Northwest. Previous research indicated that ROS melt rates were greater in a clear-cut then in adjacent forest areas. The purpose of this study was to develop a simulation model where changes in ROS melt could be predicted from the time of harvest until stand recovery. Model predictions of recovery at a point could then be extrapolated to a drainage scale permitting an evaluation of the cumulative effects of harvesting.

The initial phase of this study was a literature review examining the ROS melt process (Belt, 1996). Although there were several research studies (Coffin and Harr 1992, Berris and Harr 1987, Weatherbee 1995) contrasting differences in ROS melt between the forest and harvested areas, only one, (Hudson 1995) modeled the "hydrologic" recovery process for rain-free conditions.

The ROS melt recovery model is deterministic and reflects changes in the mass and energy balance at a point on the landscape.. Hydrometeorological variables are coupled to vegetation via changes in cover (projected canopy) which occur with time or due to harvest. The current prototype ROS model allows evaluation of recovery time differences for clear-cut, and a two-step shelterwood harvest. It can be easily extended to other harvest prescriptions where cover can be estimated from harvest to mature forest.

Data used in this study included hydrometeorological data obtained by Weatherbee (1995) estimates of cover obtained from Moeur's (1988) extension of the Stand Prognosis Model, and estimates of canopy solar radiation transmission factors presented in Reifsnyder and Lull (1965). Regrettably, these data were from different geographical locations and species and hence are used here to demonstrate and test the model.

The ROS melt model using 24-hr segments of Weatherbee's data shows recovery curves where energy and melt increase up to seven times their pre-harvest rates immediately following harvest and slowly declines to pre-harvest levels in a period of about 65 years.

The duration of the recovery periods estimated in this study are determined primarily by the changes in cover with time entered into the program. Therefore it appears that the recovery period can be estimated without the ROS model using changes in cover with time. However, melt is determined by the interaction of both cover and hydrometeorological data with the latter determining the magnitude of melt rates.

Good results were obtained comparing results of the point mass and energy balance subroutine. Data to test the recovery module was not found. Recommendations for further development of the ROS melt model towards an operational tool appear in section 6 of the main report

2.0 Introduction

This rain-on-snow melt (ROS) study has two goals: (1) document information regarding rain-on-snow melt using the literature and (2) develop a prototype model for prediction of ROS melt recovery. From an operational perspective, the purpose is to predict the time in years required for harvested areas, enhanced by rain ROS melt, to "recover" or return to their pre-harvest melt rate. Improved prediction of ROS melt recovery periods should permit better estimation of cumulative watershed effects, particularly in the prediction of peak stream flows.

2.1 Purpose

The ROS melt recovery model, ROSMOD, was developed as a prototype simulation model for two reasons. First, the prerequisite literature review (Belt, 1996) would depict the current state of knowledge regarding physical and vegetative processes involved . Secondly, modeling would provide further insight into the availability of both data and algorithms required for simulation.

2.2 Importance of ROS Melt

Rainfall on snow packs, or rain-on-snow (ROS), refers to conditions where rainfall is delivered to snow packs and melt occurs primarily due the transfer of sensible and latent heat from warm air to the snow. ROS events often occur as warm and cold fronts alternatively move through forested regions. Such events are common in the Pacific NW during the late fall, winter and spring and occur in transient snow zones which vary in elevation but typically occur between 450 and 1200 meters. They have caused severe damage due to rapid snowmelt and subsequent flooding in the western Oregon Cascades, in Northern California, and in the inland Northwest.

Substantial evidence exists that snowmelt rates are greater in natural openings or clear-cuts then adjacent forested areas during ROS events (Beaudry 1984, Berris and Harr 1987, Coffin, and Harr 1992). Only a single study by Hudson (1995) was found that addressed hydrologic recovery . Unfortunately, Hudson reported recovery in terms of snowpack water equivalent with time expressed in terms of tree height and for rain-free events. This made direct comparisons with the current study difficult. Hudson did present his data in a "natural growth model" of the form $Y = a\,(1-e^{-bx})$ where Y is the water equivalent at tree height X , and a and b are parameters determined by regression.

Removal of timber alters the site mass and energy balance by increasing radiant energy and average wind speed near the snowpack surface as well as eliminating energy involved in canopy interception loss. The net effect of these changes is to expand the energy supply at the snow surface, increase convective heat exchange, and enhance the rate of ROS melt. This means that harvesting timber can enhance the rate of ROS melt and subsequent runoff. The increase in ROS melt will diminish as the trees develop sufficient canopy foliage to shelter the snowpack from wind, reduce radiation received at the snow surface, and produce interception loss. Recovery is complete when the enhanced ROS melt rate decreases and approximates its pre-harvest level.

3.0 Rain-on-Snow (ROS) Melt Recovery Model

The ROS melt recovery model predicts changes in snow melt over time based on stand variables, principally, cover and hydrometeorological variables measured below a forest stand. These latter variables include air temperature, relative humidity, canopy cover, wind speed, incident solar radiation and precipitation. These data plus changes in cover with time, allow calculation of melt rates and recovery periods.

Design of the ROS melt model incorporates two basic ideas; (a) calculation of melt at a point on the landscape using mass and energy balance relationships, and (b) Estimation of ROS melt recovery based on changes in melt over a 100 year interval. Accordingly, the ROS melt model consists of two modules.... The point mass and energy balance subroutine and the Recovery module.

Physical processes simulated in the ROS mass and energy balance subroutine follow the work of E. A. Anderson (1976) who used a point, mass and energy balance model to estimate snowmelt. The point energy balance is used to calculate and partition energy available from the environment into melt, radiation, sensible and latent heat and precipitation. The point mass and energy balance subroutine described here simulates melt under both ROS and rain-free conditions. It does not simulate water storage within the snowpack or routing of melt water within a drainage. Effects of harvest and regeneration on the mass and energy balance, and subsequent melt, are reflected in changes of canopy cover and hydrometeorological variables.

Recovery is defined here as that point in time when enhanced melt following harvest decreases to its pre-harvest level. ROS melt recovery is modeled for ten-year intervals over a recovery period starting after harvest and continuing until ROS melt approaches its pre-harvest level.

ROS melt is simulated using the same 24-hour design storm throughout the recovery period. A design storm is an arbitrarily selected hydrometeorological data set which is representative of desired conditions, e.g. low precipitation, above average wind speeds and air temperatures above 5 degrees centigrade. Several design storms can be used to determine how different storm conditions influence the melt rate during recovery. Use of a single design storm makes the energy balance and recovery process more dependent on forest harvest and regeneration rather than changes in hydrometeorological data from year to year. Canopy cover was used to simulate changes due to harvest and regeneration. Stand growth models were used to estimate cover changes.

The ROS melt model calculates percent recovery at 10-year intervals throughout the recovery period. Recovery of the ROS melt rate is estimated using energy available for melt, expressed as water equivalent. The ROS melt program displays changes in energy supplied to the snowpack in both tabular and graphic form.

3.1 Design Features

Previously formulated simulation models describing ROS and rain-free melt were reviewed (Belt 1997) to identify alternative methods and variables. In this study a special effort was made to couple forest harvest and regeneration to ROS melt via the energy balance. Relationships linking mass and energy balance processes to vegetation were incorporated where necessary relationships and parameters were available. The model includes the following features:

- Calculation of rain and snow distributions above and below the canopy using a mass balance
- Calculation of solar radiation using an energy balance
- Simulation of changes in vegetation due to harvest using cover.
- Assessment of heat lost from the snowpack
- Determination of heat available for melt using the surface mass and energy balance
- Evaluation of the mass and energy balance of undisturbed, clear-cut and partially harvested forest.
- Graphic or tabular determination of the recovery period and display of mass and energy sources for melt.

3.11 Data

Data used to evaluate the ROS model was obtained from several sources. The hydrometeorological data came from NE Oregon, and the cover (canopy closure) relationships were based on Idaho data.

Hydrometeorological data were obtained from the work of Paul Weatherbee (1995). Weatherbee reported hydrometeorological data for ROS events at seven sites in the North Umpqua Basin located NE of Rosberg Oregon. Data collected at these sites and used in the ROS point mass and energy balance routine included : air temperature, wind speed, incoming solar radiation, relative humidity, precipitation, and snowmelt. All measurements were made below the canopy. An average value of canopy closure or "cover" was also reported for each site. These cover measurements were appropriate for the measurement period when the hydrometeorological data were observed. Vegetation at these locations consisted of a Douglas Fir, Western Larch and Grand Fir overstory and an understory of Engelman Spruce. Data from nine 24-hr ROS events were reported.

Several published relationships were utilized in the model to (1) relate changes in forest properties to time over a 100 year period and (2) relate canopy transmission of solar radiation to cover. The cover-time relationships were read into the program while the cover-transmission relationship was accessed with a table "look-up" subroutine.

Change in cover with time is a key relationship in the ROS recovery module. Changes in cover by decade, for a 100 year period, were obtained for clear-cut and two-step shelterwood harvest systems from a simulation using "Cover", an extension of the USDA-FS Stand Prognosis Model (Moeur 1985). Unfortunately, these data were derived from measurements of interior Douglas Fir on the Nezperce National Forest in Idaho rather than the coastal Douglas Fir where the hydrometeorological data were obtained.

Changes in cover with time for both clear-cut (CC) and two-step Shelterwood (SW) harvests appear in Figure 1. Prior to harvest, cover was 60 percent. Immediately following the harvest at year zero, cover was zero. Cover in the clear-cut then increased with a maximum cover value at 80 years. Note that the shelterwood harvest follows the same pattern except two cuts were made: one in year -10 and a second in year 10. This shows the effects of thinning and regrowth on cover. Also note that cover for the Shelterwood exceeds that for the clear-cut after 20 years indicating reduced melt in comparison to the clear-cut melt rates. These relationships between cover and time shown

in Figure 1 were obtained from "Cover" (Moeur 1985) , a sub-model of the Stand Prognosis model.

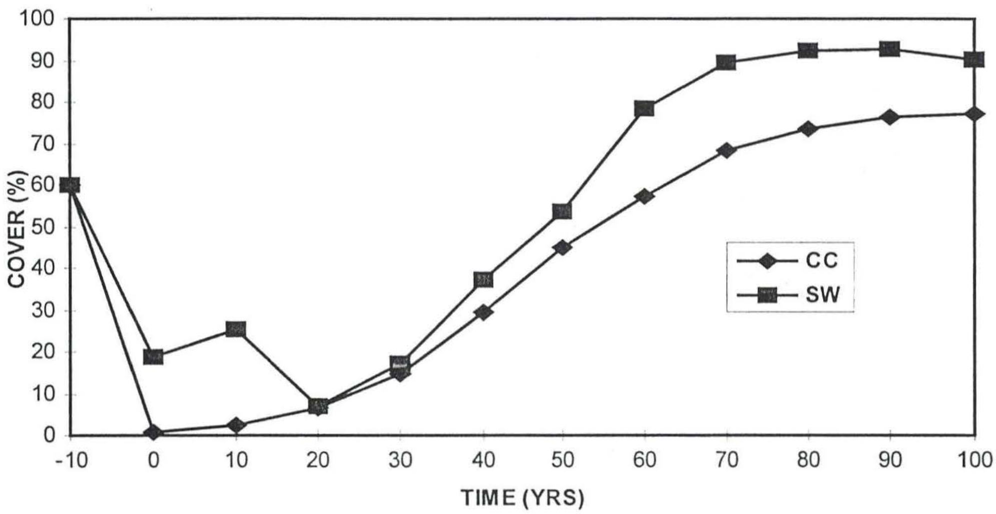

Figure 1. Changes in cover, due to harvest and regeneration, with time. The line with the diamonds represents a clear-cut; the line with boxes the two-step shelter wood thinning.

Another key relationship used in the model related transmission of solar radiation and cover as shown in Figure 2. This relationship was included in the model using data reported by Reifsnyder and Lull. (1965). These data were used to convert below canopy measurements of solar radiation to above canopy estimates which could be used on clear-cut and shelterwood sites during the decade following harvest.

A first approximation relationship between wind speed in a forest to that in a forest opening is presented by Dunn and Leopold (1976) and the USACE (1956). The wind speed transfer function is given as: Ufor = Uopen(1-.8F). The term Ufor is forest wind speed, Uopen is wind speed in an opening and F is the amount of canopy cover. In this study wind speed was first corrected using an equation obtained by Weatherbee (1995) and then utilized in the wind speed transfer function.

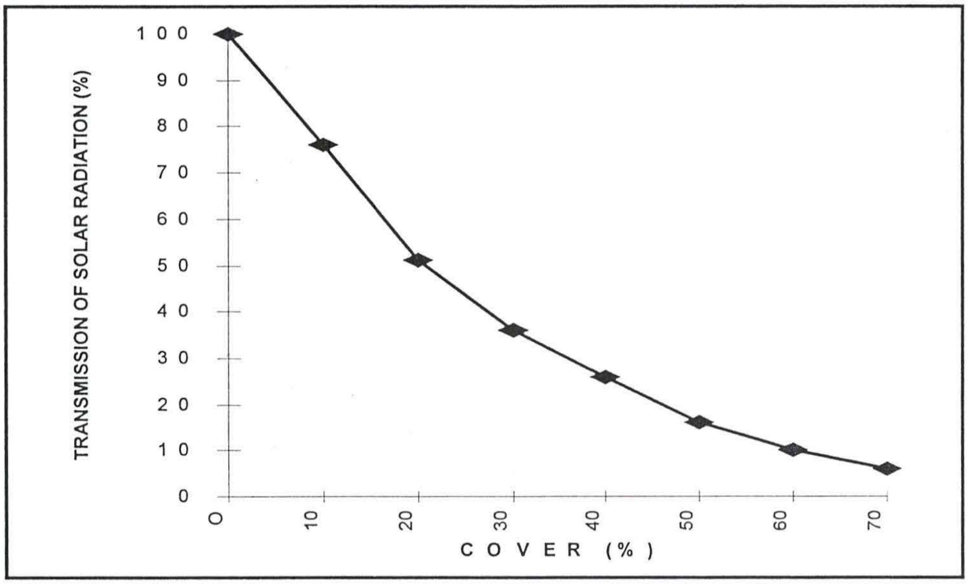

Figure 2. Solar radiation transmission through the canopy as a function of cover after Reifsnyder et al. (1965)

3.12 Design Storm

Ideally, simulation of ROS recovery periods would be based on long-term (60-100 years) continuous sequences of hydrometeorological and harvest regeneration data so that recovery would occur in response to natural ecosystem changes. Unfortunately, such records do not exist. However, if they were available, use of long-term sequences would mean the length of the recovery period would be influenced by storm characteristics such as, rainfall intensity, air temperature, relative humidity, wind speeds and storm duration. The affects of harvest on ROS melt recovery would then be partially masked by meteorological conditions which varied throughout the recovery period.

An alternative approach used in this study to circumvent the above problem, is use of the design storm concept, where available data from a particular storm or ROS event is used throughout the recovery period. As used here, a design storm is a set of hourly hydrometeorological observations which vary with time as described above but are applied to each decade throughout the recovery period. Storms used to validate this study were obtained from Weatherbee (1995) and were 24 hours in duration.

3.13 Estimating Melt in Forest Openings and Harvested Areas

Natural forest openings as well as clear-cuts and Partial cuts, e.g.. shelterwood cuts alter the energy balance between the forest the, atmosphere and the snowpack. The principal stand variable controlling energy and mass exchange above the snowpack in this model is cover.

A primitive climate model was devised to extrapolate the hydrometeorological data obtained below the forest canopy to an adjacent harvest area. This involved the following actions:

1. Determining above canopy solar radiation suitable for an open sight by extrapolating the below canopy short wave measurement to an above canopy magnitude using the canopy transmission percentage as a function of cover.
2. Altering long-wave radiation to the harvested area by omitting incoming, long wave radiation from the canopy. This occurred only when there was a difference between the vegetation and cloud base temperature used.
3. Increasing wind speed in the harvest area with a published wind transfer function relating wind speed below a forest canopy to that in the open.
4. Determining precipitation for the harvested area using a canopy mass balance where gross precipitation is first determined above the forest stand .
5. Reducing relative humidity in the harvested area by assuming air temperature is increased in the harvested area and vapor pressure is the same as in the forested area.
6. Raising air temperature in the harvest area, using *Weatherbee's data from adjacent harvested and "undisturbed" stands.

In the model actions described above one through four were always used in the mass and energy balance calculations, while actions five and six were used on an optional basis.

Figure 3 shows predicted and measured air temperature relationship. The predicted air temperature relationship is expressed as a linear model where $Tair_H = 1.52(Tair_F) + .42$ where $Tair_H$ is the air temperature in a harvested area and $Tair_F$ is the air temperature in a forest. The R^2 for this equation is 0.94.

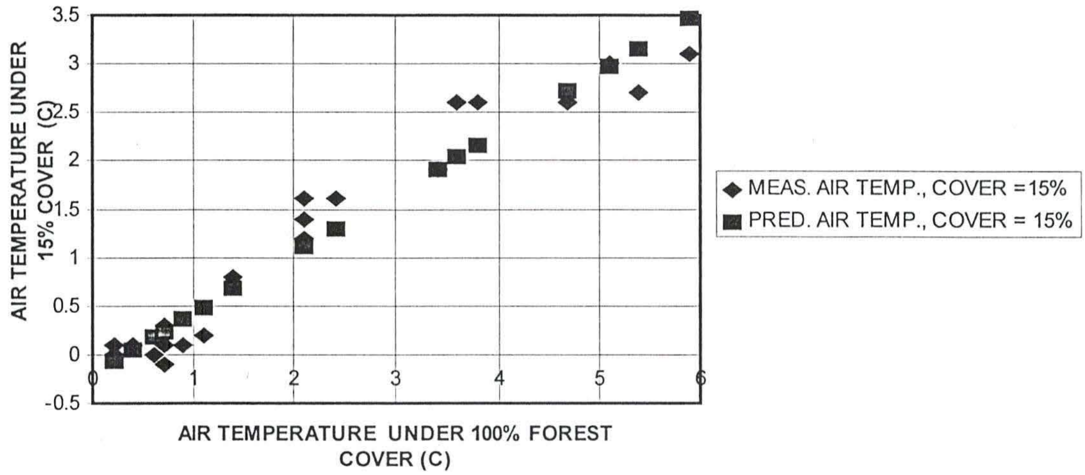

Figure 3. Comparison of measured and predicted air temperature in a forest opening where cover = 15 percent with air temperature in a forest, cover = 100 percent

3.2 Overview of the Program and Subroutines

The ROSMOD program is coded in Microsoft Quick Basic, version 4.5. It consists of nine subroutines accessed via the main program, ROSMOD.EXE. The program will run on a 386 PC or more powerful computer with a DOS or Windows operating system. A compiled copy of the ROSMOD program and a listing of the Quick Basic code are provided on a disk with this report. The following description gives a brief overview of the program by relating and describing its more important subroutines. A detailed description of the physical process modeling follows in Section 4 of this report. Figure 4 is a flow chart illustrating relationships between the main program and the principal subroutines.

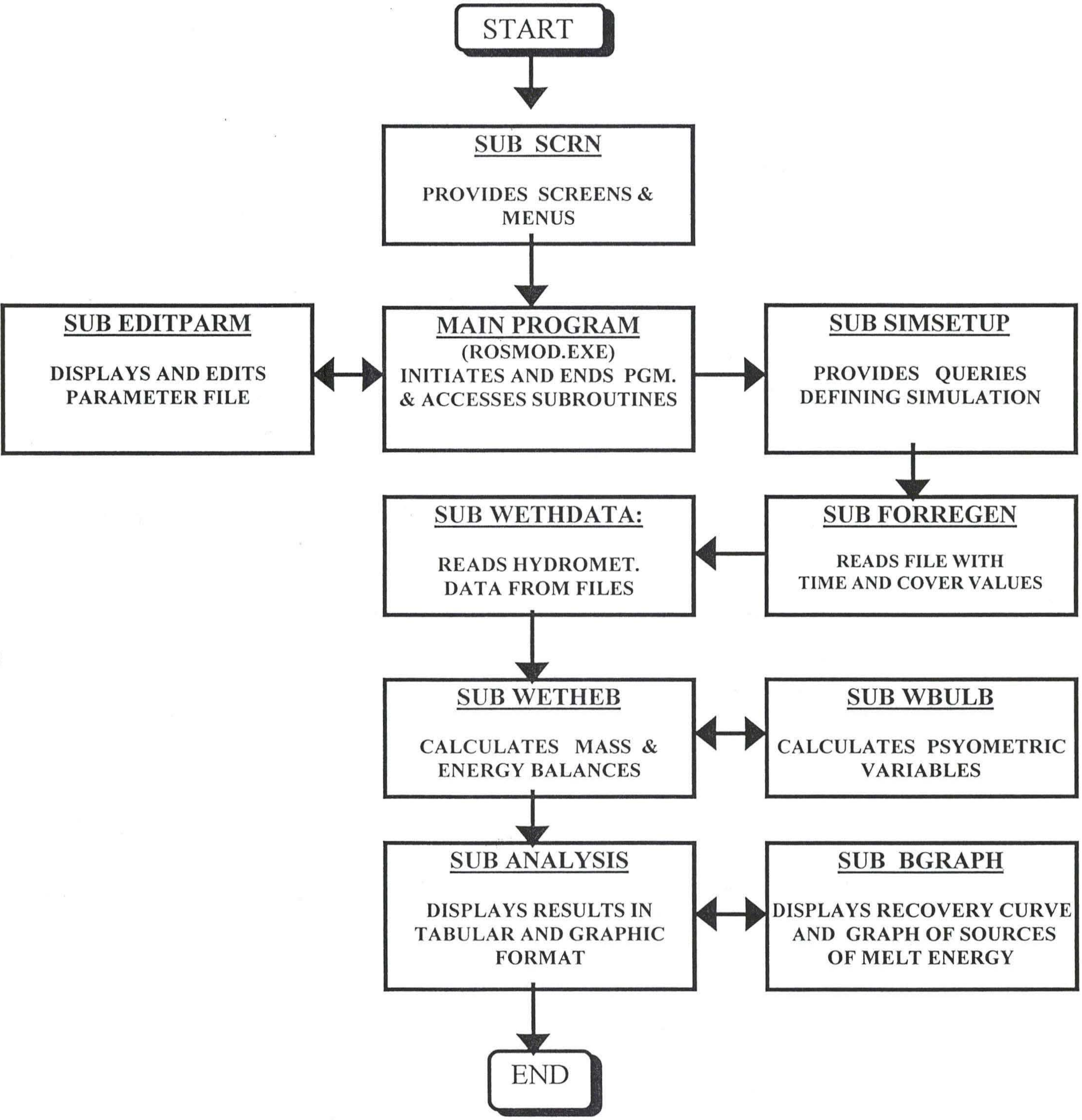

Figure 4. ROSMOD.EXE Flow diagram indicating the principal subroutines and their functions. The subroutines are further described below.

3.21 Main Program (ROSMOD15.EXE) The main program orders subroutines in appropriate sequence and provides a menu for operating the program via keyboard entry.

3.22 Simulation Control (SUB SIMSETUP) Allows keyboard entry to a) select a hydrometeorological file b) specify the harvest-regeneration method to be simulated and c) choose to use or omit the microclimate model for harvested areas.

3.23 Hydrometeorological Data (SUB WETHDATA) This subroutine reads the meteorological data and converts the dimensions as necessary.

3.24 Regeneration Data (SUB FORREGEN) This subroutine reads data describing changes in canopy cover with time. It allows the user to utilize local forest cover data and harvest methods if they can be expressed as cover. The relationships used in this model were obtained from the USDA-FS Stand Prognosis Model (Stage 1973) and its extension (Moeur 1985). Data used in this study also appear in Figure 1 below.

3.25 Mass and Energy Balance (SUB WETHEB) This is the basic module used for calculation of ROS melt. It simulates changes in the energy and mass balance with time resulting from changes in the hydrometeorological and harvest-regeneration data. The Mass and Energy Balance subroutine also accesses the Interception and Precipitation subroutine, (SUB INTERPPT) to determine the quantities of rain, snow and interception loss. The Mass and Energy Balance subroutine then calculates mass and energy balance components for each hour in the design storm. Summation of these hourly calculations over the period of the storm , provides an estimate of the energy available for melt. This melt energy is assumed representative of a ten-year period during the recovery interval.

3.26 Interception and precipitation (SUB INTERPPT) This subroutine evaluates a stand mass balance . Precipitation is partitioned into rain or snow and interception (evaporation from the canopy). Gross precipitation, throughfall, drip, and net precipitation are also calculated. Gross precipitation is used as the amount of precipitation for a forest opening or an adjacent harvest area.

3.27 Analysis (SUB ANALYSIS) This subroutine provides several tables and a graph displaying the input and calculated data. Subroutine Bargraph is accessed via the Analysis subroutine and allows review of the mass and energy balance results from several perspectives. The energy and mass balance data used to estimate melt are also

presented in tabular and graphic format. Further, a bargraph showing the sources and sinks for the melt energy is presented to allow further analyses. The ROS melt recovery period can be determined by graph or table to within 5 years.

3.4 Variables and Parameters

From a modeling perspective, state variables in the ROS melt model are snowmelt and forest cover. Snowmelt is expressed by a surrogate variable, the net energy supplied to the snowpack which is then converted to water equivalent expressed as cm of melt. The vegetated state is defined by the forest cover. The model is driven by environmental variables.... precipitation, wind speed, air temperature, solar radiation and vapor pressure. These variables are used to calculate the net energy input to the snowpack which result from mass, latent, sensible and radiation heat transfer processes. The initial state of the model occurs when harvest causes an abrupt increase in melt. The recovered ROS-melt state occurs when the ROS melt energy supply in the harvested area declines to approximately to the pre-harvest rate. Descriptions showing how the variables and parameters were used in the mass and energy balance appear below.

4.0 Energy Balance Calculations

The section describes subroutine (WETHEB) which simulates hourly mass and energy balances .

4.1 Mass Balance: Interception and Precipitation

There are no generally accepted algorithms for estimating interception loss. The algorithm used in this model and described below is based on a mass balance. The model first determines whether precipitation is occurring as rain or snow and then calculates net precipitation as shown below.

Calculations in this subroutine determine if hourly precipitation, PPT(HR), is occurring in the form of rain or snow based on air temperature. The "critical" air temperature is 273.16 degrees Kelvin. This allows separate calculation of energy added to the pack through heat and mass transfer. The critical temperature relationship is taken from the USACE (1956) .

When TAIR(HR) > 273.16 then PPT = rain
When TAIR(HR) <= 273.16 " PPT = snow

Where TAIR(HR) = Air temperature below the forest canopy (^oK)
PPT(HR) = precipitation below the canopy (cm)

Since precipitation measurements were taken below the canopy, they are net measures of precipitation, i.e., gross precipitation less interception. The sum of throughfall plus drip have the same value . The mass balance used in the model to obtain an estimate of gross precipitation for extrapolation to harvested areas is:

GROPPT(HR) - TFALL(HR) - INTFOR(HR) - DRIP(HR) = 0

The mass balance components calculated are:

GROPPT(HR) = NETPPT(HR) / ((1 - FA(YR)) + ((1 - PCT) * FA(YR)))
TFALL(HR) = GROPPT(HR) * (1 - F(YR))
DRIP(HR) = GROPPT(HR) * (1 - PCT) * F(YR)
INTFOR(HR)= PCT * GROPPT(HR) * F(YR)
NETPPT(HR) = TFALL(HR) + DRIP(HR)

Where: FA = cover provided by canopy during the period when hydrometeorological measurements were made (%).
NETPPT(HR) = precipitation measured below the forest (cm)
PCT = assumed percent of gross precipitation lost to evaporation a value of 15 percent was used (cm).
DRIP(HR) = precipitation reaching the forest canopy not evaporated as interception (cm)
F(YR) = cover during a single 10-yr portion of the recovery period (%)
INTFOR(HR) = precipitation evaporated from the canopy(cm).
TFALL(HR) = throughfall from areas with no cover (cm).

4.2 Energy Balance

The energy balance subroutine calculates the heat energy balance at a point within the forest or within a harvested area based on measured hydrometeorological data.

4.21 Point Energy Balance

Mass and energy balances calculated for each of the 24 hours in a data set. The hourly data provided by Weatherbee (1995) was observed in forested stands except for a single case in which the solar radiation data was flawed apparently due to snow on the solarimeter. Since the recovery period involves a period of harvest where cover approaches a minimal value (zero in the case of a clear-cut), it is necessary to estimate the energy balance in the harvested area by extrapolating from the forest measurements. Melt is calculated in both cases assuming a ripe snowpack. The equation for the mass and energy balance is:

$$\mathrm{MELT(HR)} = \mathrm{RN(HR)} + \mathrm{H(HR)} + \mathrm{LE(HR)} + \mathrm{RAINCAL(HR)} + \mathrm{SNOWCAL(HR)} + \mathrm{CLDCONT(HR)}$$

Where:
Rn(HR) = net radiation (cal/cm2-hr)
H(HR) = sensible heat (cal/cm2-hr)
LE(HR) = latent heat (cal/cm2-hr)
RAINCAL(HR) = advected heat from rain (cal/cm2-hr)
SNOWCAL(HR) = advected heat from snow (cal/cm2-hr)
CLDCONT(HR) = latent heat released from the snowpack (cal/cm2-hr)
HR = the 60-minute period to which observations apply

Equations for calculation of the above energy balance components follow.

4.22 Heat and Mass Transfer Functions

Wind speed was observed below the forest canopy and wind speed for a harvested area was approximated using the relationship UCC(HR) = UFOROBS/ (1 - .8F), where:

UFOROBS = wind speed measured below the forest canopy (m/s)
UCC(HR) = Wind speed estimated for harvested opening. (m/s)

Wind speed estimates were then used to obtain empirical wind transfer functions for latent and sensible heat as outlined by Anderson (1976). Preference for using wind transfer functions instead of eddy transfer coefficients, is the low expectation of the snow surface boundary layer within a forest meeting the necessary boundary-layer assumptions i.e., full development, steady-state or logarithmic wind profile. Also wind below the canopy is coupled to that above by large scale vertical flows moving in and out

through canopy openings. Empirical wind transfer functions are calculated as shown below.

Weatherbee (1995) examined below canopy forest wind speeds predicted by Dunn and Leopold (1978) in equation (H1) below. He reported that equation (H1) underestimated wind speed below the canopy and developed equation (H2) showing the correction. Equation H3 combines equations H1 and H2 relating observed forest wind speed below the canopy to that in a harvested area, UCC(HR)

$$UFOR(HR) = UCC(HR)\,(1-(.8F(HR))) \qquad H1$$
$$UFOR(HR) = .56(UFOROBS(HR)) + .55 \qquad H2$$

$$UCC(HR) = (.56(UFOROBS(HR)) + .55) / (1-(.8FA(HR))) \qquad H3$$
$$UFOR(HR) = UCC(HR)\,(1 - (.8F(HR)) \qquad H4$$
$$WTFOR = (UFOR(HR)/1000)(3600)\,DT \qquad H5$$
$$WTCC = (UCC(HR)/1000)(3600\,DT) \qquad H6$$
$$FU\,(HR) = A\,COEF + BCOEF(WTFOR)/10 \qquad H7$$
$$FUCC(HR) = ACOEF + BCOEF(WTCC)/10 \qquad H8$$

Where:

ACOEF = Intercept in equation X7, (mm/mb) ACOEF = 0
BCOEF = slope in equation X7, (mm/mb-km) BCOEF = .002
DT = is the time interval between data measurements (hr)
F(HR) = Cover value for single interval during recovery period (%)
FA(HR) = Cover during the time of data measurement (%)
FU(HR) = Wind transfer function below forest canopy (mm/mb)
FUCC (HR) = Wind transfer function (mm/mb)
UCC(HR) = Adjusted wind speed in harvest area (m/s)
UFOR(HR) = Adjusted wind speed below canopy (m/s)
UFOROBS(HR) = Observed wind speed below canopy (m/s)
WTCC = Wind travel function in harvest area (km)
WTFOR = Wind transfer function below forest canopy (km)

4.23 Sensible and Latent Heat Transfer Functions

Sensible and latent heat exchange are driven respectively by differences in air temperature and vapor pressure between the snow surface and the air near the surface. The transfer function FU is calculated from wind velocity as shown above.

4.24 Sensible and Latent Heat

Driving variables in sensible heat calculation are air temperature and the transfer function, FU(HR). TSNOW is a constant at 273.16 K. The equation for sensible heat exchange is :

H(HR) = (LESUB (RHOW)/ 10) (GAMMA)FU(HR)(TAIR(HR) - TSNOW)

Where:

GAMMA =CP* PAIR / (E*LESUB)
RHOW = Density of water vapor (gms/cm3)
CP = specific heat of air (cal/gm-K)
E = ratio of molecular weight of water to molecular weight of dry air (0.622)
PAIR = air pressure (mb)
FU(HR) = wind travel function in the forest (km)
FUCC(HR) = wind travel function for harvested area (km)
Tsnow = snow temperature (K)
TAIR(HR) = air temperature (K)
LESUB= latent heat of sublimation

Latent heat transfer is determined by:

LEFOR(HR) = LESUB(RHOW)/ 10) FU(HR) (EAIR(HR)- ESNOW)

EAIR(HR) is the vapor pressure of the air calculated from observed air temperature and relative humidity using:

ESAT(HR) = 10 * (EXP(52.57633 - (6790.4985 / TAIR(HR)) - (5.02808 * LOG(TAIR(HR))))) (mb)
EAIR(HR) = ESAT(HR) * RH(HR) (mb)

Where:

LEFOR(HR) = latent energy exchange at the snow surface (cal/cm2-hr)
EAIR(HR) = vapor pressure of the air (mb)
ESNOW= vapor pressure of snow (mb)_
ESAT(HR) = saturated vapor pressure of air (mb)

LESUB = latent heat of sublimation with a value of 677 (cal/cc)
RHOW = density of water (gm/cc)

4.25 Solar Radiation

Solar or short-wave (SW) radiation below the forest canopy was measured directly and represents the sum of incoming direct and diffuse radiation. In order to estimate gross solar radiation above the canopy, a SW energy balance, along with a cover dependent transmission factor, was employed.

Gross solar radiation estimates above the canopy are needed to determine the SW radiation on harvested areas. Gross radiation is calculated using canopy transmission factors, TRAN(YR). Transmission factors range from zero with no transmission to one with complete transmission (Reifsnyder and Lull 1965).

Gross solar radiation is calculated using a transmission factor and cover, 'FA', appropriate to the time of measurement. When SW is calculated using equation 5b, a cover value of 'F' is used which is appropriate to the time interval in the recovery period. The procedure described in equations 5a-5c (1) estimates gross solar radiation based on data from the data observation period (2) provides gross radiation values needed in harvested areas and (3)casts the SW energy analysis into an energy balance format.

$$GROSW(HR) = SWIN(HR) / TRAN(YR, FA) \qquad 5a$$
$$SW = GROSW(HR) * TRAN(YR, F) \qquad 5b$$
$$SWNET(HR) = SW * (1 - ALBEDOS) \qquad 5c$$

Where ALBEDOS = snow albedo, an estimate of reflected SW energy(%)
SWNET(HR) = net solar radiation to the snow surface (cal/cm2-hr)
SWIN(HR(HR) = incoming solar radiation to the snow surface (cm/cm2-hr)
SW = dummy variable

4.26 Terrestrial Radiation

Terrestrial or long-wave (LW) radiation is emitted from several sources. Four sources are included in this simulation... clouds, the atmosphere, the forest canopy and the snowpack.

Emissivity of the air above the snowpack and cloud base can be estimated using several equations (Campbell, G. 1977, Bonan 1991 ,Wetherbee 1995). Equations 4a-4b

were used in this simulation because of their relative simplicity and accuracy. Note that cloud Emissivity, EMISCLD, was entered as a parameter as was the difference between surface and cloud base temperatures, CLDT. In this model CLDT was set to zero. The equations below show how LW radiation was calculated for the snow surface below a forest canopy. These same equations, with the equation R3 removed or set to zero, are used for harvested area calculations.

EMISAIR = 1 - .261 * EXP(-.000777 * (273 - TAIRCC(HR)) ^ 2 (%) R1
EMISSKY = ((1 - C) * EMISAIR) + C * EMISCLD (%) R2
LWINVEG = F(YR) * SBOLTZ * EMISVEG * (TAIR(HR) ^ 4) R3
LWIN = LWINVEG + (1 - F(YR)) * SBOLTZ * EMISSKY * ((TAIR(HR) - CLDT) ^ 4) (cal/cm2-hr) R4
LWOUT = -1 * EMISNOW * SBOLTZ * (TSNOW ^ 4) R5
LWNET(HR) = LWIN + LWOUT R6

Where:
SBOLTZ = Stephan-Boltzmann constant (4.8792E-09)
C = percent cloud cover expressed as a decimal
CLDT = estimated difference between TAIR and cloud base temperature (K)
EMISAIR = emissivity of air under clear sky (fraction 0-1)
EMISCLD = emissivity of air under cloud cover (fraction 0-1)
EMISNOW = emissivity of snowpack at zero degrees C (fraction 0-1)
ESAT(HR) = saturated vapor pressure of air (mb)
LWIN(HR) = LW energy supplied to snow pack (cal/cm2)
LWOUT(HR) = LW energy emitted by the snowpack (cal/cm2)
LWNET(HR) net LW radiation to snowpack (cal/cm2)
RH (HR) = relative humidity of air expressed as a decimal
TAIR(HR) = air temperature below forest canopy (K)
TSNOW = Temperature of snow (K)

4.27 Advection of Rain and Snow

Mass added to the canopy from precipitation or lost from the canopy via interception (evaporation) and drip) are calculated based on net precipitation calculated in 4.1 above .

ERAIN(HR) = CPW * RHOW* (TAIR(HR) - 273.16) * NETPPT(HR)

ESNOW(HR)= CPS * RHOS* (TAIR(HR)- 273.16) * NETPPT(HR)

Where:

CPW = specific heat of water (cal/gm-K)
CPS = specific heat of snow (cal/gm-K)
ERAIN(HR) = advected energy gained from rainfall (cal/hr)
ESNOW(HR) = advected energy gained from snowfall (cal/hr)
RHOW = density of water (1 gm/cc)
RHOS = density of snow (0.5gm/cc)
TAIR(HR) = temperature of air (K)
NETPPT(HR) = rain or snow falling to the snow surface (cm)

4.3 Harvest and Regeneration

Harvest and regeneration are simulated by changes in canopy cover, "F", with time. A file is opened and values for cover are read as percents and time is read in 10 year intervals. Changes in cover are arranged in the file so that canopy density during the first decade (-10 TO 0) is representative of pre-harvest stand conditions and during the second decade (0 TO 10) cover, is representative of a natural forest opening, or a clear-cut stand, i.e., F => 0. Subsequent values of cover increase with time , by decade, assuming no additional harvesting. These values are used to express stand changes for each decade during the recovery period.

5.0 Model Testing

The ROS model was tested in two steps: (a) validation of the physical processes incorporated in the mass and energy balance subroutine by comparison with similar predictions from a well known melt model (Anderson 1976) and mass balance calculations made by Wetherbee (1995) and (b) Analysis of the ROS melt recovery module based on the 24-hr data sets reported by Wetherbee (1995).

5.1 Validation of the Mass and Energy Subroutine

Good agreement was obtained between the ROS melt model predictions and melt predictions using Anderson's (1976) model. This is expected since the ROS point mass and energy balance subroutine is a modified form of a melt model developed by Anderson.

There are a number of differences between these models . First, the mass and energy balance subroutine was designed so that predictions of melt could be made for various conditions such as natural forest openings, clear-cut areas and partially harvested areas, e.g., shelterwood thinnings. This requires a knowledge of cover at the time of harvest and changes in cover over a 50-100 year recovery period as well as cover at the time when the hydrometeorological data were obtained. Second, interception was estimated and a mass balance was devised to estimate gross precipitation in an opening from measurements of net precipitation in an adjacent forest stand. The solar radiation balance was formulated using an energy balance where differences between gross and net solar energy were determined using a canopy transmission coefficient. Use of the transmission coefficient circumvented the need to use leaf area index (LAI) and facilitated extrapolation of solar radiation to clear-cuts and natural openings. This is an important difference since LAI data are limited and the published transmission percentages (Reifsnyder and Lull 1965) are more readily available.

Finally differences in wind speed between open and forested areas were obtained using a corrected form of the equation UFOR = UCC (1- .8F) provided by Wetherbee (1995).

The ROS mass and energy balance subroutine was tested by comparison with Anderson's snow melt model and mass balance measurements made by Wetherbee (1995). Nine of Wetherbee's (1995)data sets containing 24-hr ROS data were used . Results of the comparison are summarized in Table 1.

Table 1 Comparison of melt estimates and related variables for nine 24-hr ROS periods based on data from Wetherbee (1995) . See Table notes below for clarification.

1	2	3	4	5	6	7	8	9
DATA SET & EVENT	WETH COVER F%	ROS NET PPT	ROS PRED. MELT	ROS MELT + PPT	WETH LYSIM. OUT	WETH. LYSIM. - PPT	ANDERSON MELT	MELT + PPT
1 (1-1)	65	2.97	0.08	3.05	2.6	-0.37	0.1	3.07
2 (1-2)	65	0.55	0.91	1.46	1.18	0.63	0.87	1.42
3 (1-3)	65	0.79	0.19	0.98	1.3	0.51	0.08	0.87
4 (2)	100	1.27	0.26	1.53	0.92	-0.35	0.45	1.72
5 (3)	15	1.1	1.77	2.87	0.6	-0.5	0.7	1.8
6 (4-1)	65	1.35	0.91	2.26	2.3	0.95	0.9	2.25
7 (4-2)	65	2.15	1.13	3.28	3.6	1.45	1.1	3.25
8 (4-3)	65	4	0.84	4.84	4.3	0.3	0.8	4.8
9 (5)	80	3.81	.O9	3.89	3.6	-0.21	0.12	3.93

Column 1 data set number used in the ROSMOD.EXE program and the ROS event. The designation 2 (1-2), refers to the second data set "2" and the (1-2) refers to the first event and the second 24-hr period in the first event.
Column 2 average forest cover reported by Wetherbee. (%)
Column 3 24-hr net precipitation below the forest canopy . (cm/24-hr)
Column 4 melt predicted by the ROS mass and energy balance subroutine. (cm/24-hr)
Column 5 ROS subroutine estimates of lysimeter outflow + precipitation. (cm/24-hr)
Column 6 lysimeter outflow as reported by Wetherbee. (cm/24-hr)
Column 7 melt calculated as the difference between lysimeter outflow and precipitation. (cm/24-hr)
Column 8 melt predicted by Anderson's model and reported by Wetherbee. (cm/24-hr)
Column 9 Anderson model estimates of total runoff, i.e., melt + precipitation (cm/24-hr)

Given dissimilar models, reasonable agreement is shown in Table 1 between melt predicted by the ROS subroutine (col. 4) and similar values obtained using Anderson's

melt model (col. 8). Similarly, there is good agreement between the ROS estimate of melt + precipitation (col. 5) and Anderson's estimate (col. 9) of the same variable. Unfortunately, neither the ROS nor Anderson's melt estimates compare well with melt estimates determined using the mass balance (col. 7) . This estimate, computed from the difference between lysimeter outflow and precipitation, reflects temporal differences in snowpack freezing, thawing and storage. However, neither the Anderson model nor the ROS model simulate snowpack heat and water storage and so the differences are expected. Negative values of melt (col. 7) occur when precipitation is greater than lysimeter outflow indicating increased storage within the snowpack.

Melt from a clear-cut is compared with that from a two-step shelterwood using ROS melt model estimates obtained using data set, 1(1-1). Note that 24-hr rates of melt are less than a centimeter. Also the clear-cut melt data appears to have the "growth" curve described by Hudson (1995) such that $M_t = M_0(1- e^{-bt})$ where M_t is the ROS melt rate at any time interval t, M_0 is the melt occurring immediately following harvest, and b is a constant.

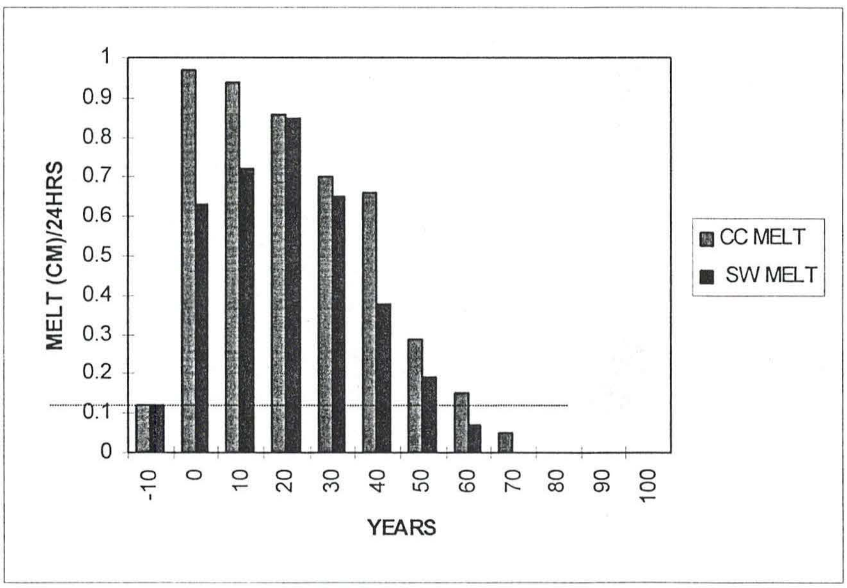

Figure 5. Changes in ROS melt due to clear-cutting (CC) and a 2-stage shelterwood (SW) for a 24-hr period during each decade of the 65 year recovery period. The end of the recovery period is indicated by the dashed line.

5.2 Analysis of the ROS Recovery Module

Mass and energy balance components , net radiation, interception, precipitation, and latent and sensible heat are coupled to changes in time by the variable, cover. The net effect is that melt decreases when cover increases. This is illustrated in Table 2 which summarizes melt during the recovery period for data sets 1 (1-1), 6(4-1) and 9 (5). Note in the last three columns of Table 2, melt returns to its pre-harvest level at 60-70 years or approximately 65 years following harvest. By definition, 65 years is the recovery period. The dotted line indicates where melt returns to its pre-harvest level . The melt rates shown in Table 2 also illustrate that the magnitude of the melt is strongly influenced by the hydrometeorological data set. The pre-harvest melt rates for the three data sets shown in Table 2. are .12, 1.02, .42. This shows that recovery can occur within the same interval but rates of melt may be quite different.

In Table 2, vegetation recovery, represented by cover (col. 2) , has a pre-harvest value of 60, then decreases following harvest and reaches its recovery state between 60-70 years, say 65 years. Using the ROS model to evaluate the nine data sets showed that the recovery period was 65 years for all data sets. This strongly suggests that the duration of the recovery period can be evaluated without reference to the ROS melt model. However, the ROS melt model allows estimation of the melt rate during the harvest period and would be needed where recovery was defined not by years but in a specified melt rate.

For example in setting criteria to evaluate cumulative effects, the criterion is that for 90% of storms melt rates should not exceed 2.7 cm/24hr.

Table 2. Recovery periods for selected data sets as indicated by melt rates

		Melt(cm/24hr)		
Years	Cover(%)	1 (1-1)	6(4-1)	9(5)
-10	60.0	.12	1.03	.42
0	1.2	.97	2.63	3.01
10	2.0	.94	2.59	2.88
20	6.1	.86	2.47	2.62
30	14.6	.70	2.21	2.07
40	29.3	.66	1.93	2.22
50	44.7	.29	1.41	.81
60	57.3	.15	1.09	.48
70	68.3	.05	.84	.27
80	73.5	0.0	.71	.17
90	76.4	0.0	.65	.14
100	77.2	0.0	.63	.12

Finally, using 24-hr segments of Weatherbee's data, the ROS melt model shows recovery curves where energy and melt increase following harvest by a factor of up to seven times their pre-harvest values.

6.0 Discussion

6.1 Design of the ROS Melt Model

A prototype ROS melt model has been designed and tested. The model has promise as an operational tool for addressing the cumulative effects of ROS melt. Point mass and energy balance subroutine melt estimates compare well with predictions from a similar model developed by Anderson (1976). Data to test the recovery module were not found. Analysis of predicted recovery intervals indicate that the recovery period can be determined based on changes in cover, but that the magnitude of the melt rate must be determined by simulation. Also an exponential equation appears to have merit in mathematically describing the decrease in melt rates following harvest.

Several techniques used in design of the ROS melt model are worthy of mention. First, the point mass and energy balance subroutine can be enhanced by increasing the coupling between the vegetation variable, cover, and the simulated energy processes. These modifications include addition of (a) a mass balance using cover, and allowing, interception loss to be estimated based on below canopy measurements of precipitation and (b) a solar radiation balance also using cover and canopy transmission coefficients to estimate above canopy radiation. Secondly the point mass and energy balance subroutine can be linked with the recovery module so that mass and energy balance estimates for a given decade can be made for specific harvesting and regeneration methods. Cover data needed to implement this feature is read from a file making it easy to change the harvesting methods used.

Finally, the ROS melt model includes a climate transfer protocol which allows prediction of melt in a clear-cut based on hydrometeorologic data from an adjacent forest stand.

6.2 Future Research and Development

Future research and development effort should address four issues.

- Revision of the current model so that it can be tested with data provided by Dr Dennis Harr. This will require more than just changing the data-entry subroutines, since the data collected by Harr is different from that obtained by Wetherbee . Consequently, some of the energy balance simulations will require alteration.
- Some better means of testing the recovery module needs to be devised. The most likely avenue is to find a means of coupling the ROS melt model with a stand growth model, e.g. the Stand Prognosis Model and the "Cover " extension.
- Further effort should be made to (a) incorporate an exponential equation into the model which will describe the decline in melt rates following harvest and (b)determine if there is a basis for classifying ROS events based on hydrometeorological data.
- The crude climate transfer protocol used in the recovery module for predicting hydrometeorological variables in an opening from those in a forest should be further tested and developed. Dr. Harr's data may be useful here.

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